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STRENGTH OF ORE AND TOP ROCK IN THE RED IRON-ORE MINES OF THE BIRMINGHAM DISTRICT, ALA.

BY

W. R. CRANE

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STRENGTH OF ORE AND TOP ROCK IN THE RED IRON-ORE MINES OF THE BIRMINGHAM DISTRICT, ALA.

By W. R. CRANE

INTRODUCTION

A wide choice of stone is usually available for building any type of structure, but the native ore and rock must form the pillars and roof in a mine. The character and condition of the ore and rock and the weight of the load to be supported are fixed; the only factors that can be varied are the dimensions of the pillars—that is, the cross-sectional area—and the height and width of openings. Evidently it is very advantageous to know as definitely as is possible the strength of the support in order that proper values may be given the variable factors. This paper presents the results of the writer's attempts to ascertain the strength of the ore and top rock in the hematite mines of the Birmingham district and to determine the size of pillars adequate to support the roof as the mines grow deeper. Surface cracks, excessive inflows of water, and the collapse of pillars have made it desirable, if not imperative, to obtain all possible information on the sufficiency of the roof support in those mines.

Among the underground conditions that were studied carefully were the failure of pillars and top rock and their relation to the occurrence of ore in the bed worked. The investigation was extended to include determination of the strength of the ore forming the pillars and of the rock of the roof formations. The results are recorded herein.

ACKNOWLEDGMENTS

Acknowledgment is made to the operators of the iron-ore mines for their cooperation. Particular acknowledgment is due to C. E. Abbott, general manager, Tennessee Coal, Iron & Railroad Co.; C. E. Bowron, chief engineer, Gulf States Steel Co.; W. M. Lacey, former general superintendent, and J. R. Moore, local superintendent of ore mines, Woodward Iron Co.; W. J. Penhallegon, general superintendent, Republic Iron & Steel Co.; J. E. Strong, vice president and chief engineer, Alabama Co.; and H. J. Thomas, general superintendent, Sloss-Sheffield Iron & Steel Co.

Special acknowledgment is due the Reed Bros. Stone & Monument Works, of Birmingham, for assistance in preparing test pieces for crushing and bending tests; to the Carnegie Institute of Technology

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and the United States Bureau of Standards for making tests in its laboratories; and to many others whose advice and suggestions have been of much value.

OCCURRENCE OF ORE AND TOP ROCK

No study of the strength of rock formations can be complete unless it includes data on the formations as they occur in place. All stratified formations may be cross-bedded in places, and the cross-bedding planes, lying at an angle with the normal bedding, may seriously lessen the strength of a rock formation. Joints or slip planes, which are often called "headings," are another source of weakness.

Slip planes usually occur in two series that cut one another at approximately right angles, and may be termed "major slips" and "minor slips." If several series are present in a bed, the bed is broken into blocks whose dimensions range from a few inches to a number of feet. At those mines in the Birmingham district where the major and minor slips correspond with the strike and dip of the beds they may materially help development and the breaking of ore, but this advantage may be more than offset by the pillars and roof being weakened and rendered more liable to fail under pressure—pillars in particular tend to disintegrate most along planes parallel to their free faces.

In the Birmingham district slip planes are seen to best advantage in the ore bed, but they occur in the top formations, where they are very persistent laterally and vertically. Both the top rock and the ore are weakened by slip planes and cross-bedding; the former are elements of inherent weakness in ore and top rock, and the latter affects the top rock most.

COMPRESSIVE STRENGTH OF IRON ORE

The load of the superincumbent formations is exerted in two ways—in compressing the ore in the pillars and in bending the top rock. The resistance to compression is the compressive or crushing strength; the resistance to bending the bending or transverse strength. The elasticity of a material under stress plays an important part in the strength of the elements of support. The strength of ore and top rock is then of three kinds—compressive, transverse, and elastic.

In the investigation of the compressive strength of ore great care was taken to obtain masses of ore that were free of flaws and fractures caused by earth movements and blasting. Sections were cut—in fact, practically sawed out—by hand-power drills at points as far as possible from drill holes and between joints or slip planes. Figure 1 shows a section of the ore bed cut out for testing. In a similar manner pieces of top rock were removed from the roof after several

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feet of top had fallen. Such pieces could not possibly have been weakened by shooting.

SIZE AND SHAPE OF TEST PIECES

The compressive or crushing strength of the ore must be the basis for determining the supporting strength of mine pillars. The collection and preparation of test pieces is therefore an important part of the work of determining the strength of ore, and great care must be taken in obtaining representative samples.

As determination of the compressive strength of each foot of the bed worked was desired, complete sections were taken and broken into foot sections, from which the test pieces were prepared. The masses of ore representing the feet in the sections were numbered

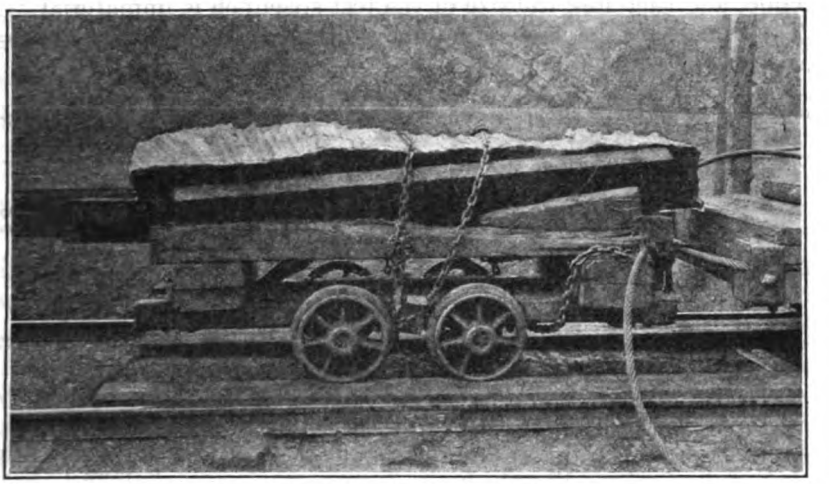

FIGURE 1.—Section of ore bed brought to surface

from the top of the bed down, the top of each section being marked to show its position in the bed with respect to bedding planes and dip.

The masses or sections of ore were then cut into cubes one-half inch oversize by gang and carborundum saws. The rough cubes were squared up and ground to hone finish on the rubbing bed, with no attempt to obtain definite sizes.[1] Although most of the test pieces were cubes, many others were of odd sizes and shapes. Results of the tests of these irregular pieces will be given separately.

EFFECT OF SIZE AND SHAPE ON COMPRESSION

Data and opinions on the effect of size and shape upon the result of compressive tests have been conflicting. In 1876 Q. A. Gilmore[2]

[1] Cubes were prepared from masses of ore through the courtesy of Reed Bros. Stone & Monument Works, Birmingham, Ala.

[2] Gilmore, Q. A., Report on the Compressive Strength, Specific Gravity, and Ratio of Absorption of the Building Stones of the United States. 1876, p. 28.

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made an extended series of tests of building stones, which seemed to indicate that the increase in resistance to crushing per square inch varied directly with the size of cube tested. The results of his tests are summarized as follows:

TABLE 1.—*Size and compressive strength of stones*

Size of cubes	1 inch	1¼ inches	1½ inches	1¾ inches	2 inches	2¼ inches	2½ inches	2¾ inches
Total	104, 500	160, 740	193, 200	313, 600	480, 100	633, 500	698, 200	
Average	9, 500	16, 074	24, 150	34, 844	48, 010	63, 350	66, 466	100, [illegible]
Square inch	9, 500	10, 300	10, 730	11, 377	12, 000	12, 500	10, 635	13, [illegible]

Doctor Baker states [1] that "It has been conclusively proved that the strength per square inch of bed area is independent of the size of cube, and therefore the size of the test specimen is immaterial."

Tests made by the writer that show similar variations in compressive strength are as follows:

TABLE 2.—*Compressive strength, in pounds, of iron-ore cubes, by mines and sizes of cubes*

Mine	Mine sample No.	Cube No. 1, 2 square inches	Cube No. 2, 4.78 square inches	Cube No. 3, 9.17 square inches	Cube No. 4, 15.97 square inches	Average for mine
B	22	9, 837				11, 775
	31	10, 789				
	16		9, 220			
	15		13, 723			
	2				13, 423	
	1				13, 660	
C	27	13, 754				14, 609
	28		10, 774			
	20			13, 439		
	11				14, 735	
	12				17, 269	
	21				17, 693	
D	14	8, 649				12, 242
	30		11, 682			
	13			14, 707		
	4				13, 817	
	3				12, 359	
F	24	8, 681				11, 709
	32	14, 652				
	6		10, 160			
	25		11, 301			
	5				13, 755	
G	23	10, 517				13, 890
	33	13, 279				
	17		17, 040			
	8			11, 638		
	7				16, 977	
H	29	11, 654				13, 574
	26	12, 101				
	19		12, 123			
	18			14, 308		
	9				16, 219	
	10				15, 042	
Average		11, 391	12, 002	13, 522	14, 994	12, 977

[1] Baker, Ira Osborn, A Treatise on Masonry Construction. 1909, p. 8.

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The percentage differences noted between Nos. 1, 2, 3, and 4 are 5, 11, and 9. Subsequent tests indicate, however, that the increase in compressive strength noted is due not so much to the large cubes actually giving increased strength as to the smaller cubes making less perfect contact with the plates of the testing machine because of difficulties experienced in cutting plane faces. (See fig. 2.)

The tests given above were made primarily to determine the size of cube most desirable for tests; as a result it was decided to use test pieces with 3 to 4 inch sides.

ADVANTAGES OF CUBICAL TEST PIECES

The cubical test piece seems to be the simplest and most readily made and is commonly used. Gilmore, speaking of tests made by Hodgkinson, says[4] that "The cubical form of specimens adopted for the experiment affords sufficient security for the angular breakage which he proved to be necessary for a true result. This latter fact is corroborated by subsequent experiments."

Doctor Baker states that although theoretically the best form of test piece should be higher than broad, it is common practice to use cubes.[5]

Doctor Parks states[6] that "A broken cube tends to assume the form of two pyramids with their apexes at the center and their bases against the bearing plates of the machine. Doctor Buckley considers these residual forms as indicative of the strength of the stone."

The consensus of opinion seems to be that good results are obtained when two pyramids are formed with their apexes centering in the cube and their bases against the plates of the testing machine. Such was true in the series of tests of iron-ore cubes. Almost invariably cubes that showed symmetrical angular fracture resulting in the above-described form had the greatest strength. However, Doctor Parks states in the above connection that "It was observed that the limestones of high strength from different parts of Ontario resulted in a series of vertical columns with scarcely any appearance of either cone or pyramid." A few of the writer's samples broke thus, but by far the most representative tests gave the pyramidal and conical forms.

METHODS OF TESTING AND RESULTS OF TESTS

The preliminary tests of iron-ore cubes, by Prof. F. A. Simmons, Carnegie Institute of Technology, Pittsburgh, Pa., were made with Olson testing machines of 20,000 and 200,000 pounds capacity,

[4] Gilmore, Q. A., Report on the Compressive Strength, Specific Gravity, and Ratio of Absorption of the Building Stones of the United States. 1876, p. 5.

[5] Baker, Ira Osborn, A Treatise on Masonry Construction. 1909, p. 8.

[6] Parks, William A., Report on the Building and Ornamental Stones of Canada: Canada Department of Mines, Mines Branch, 1912, vol. 1, p. 46.

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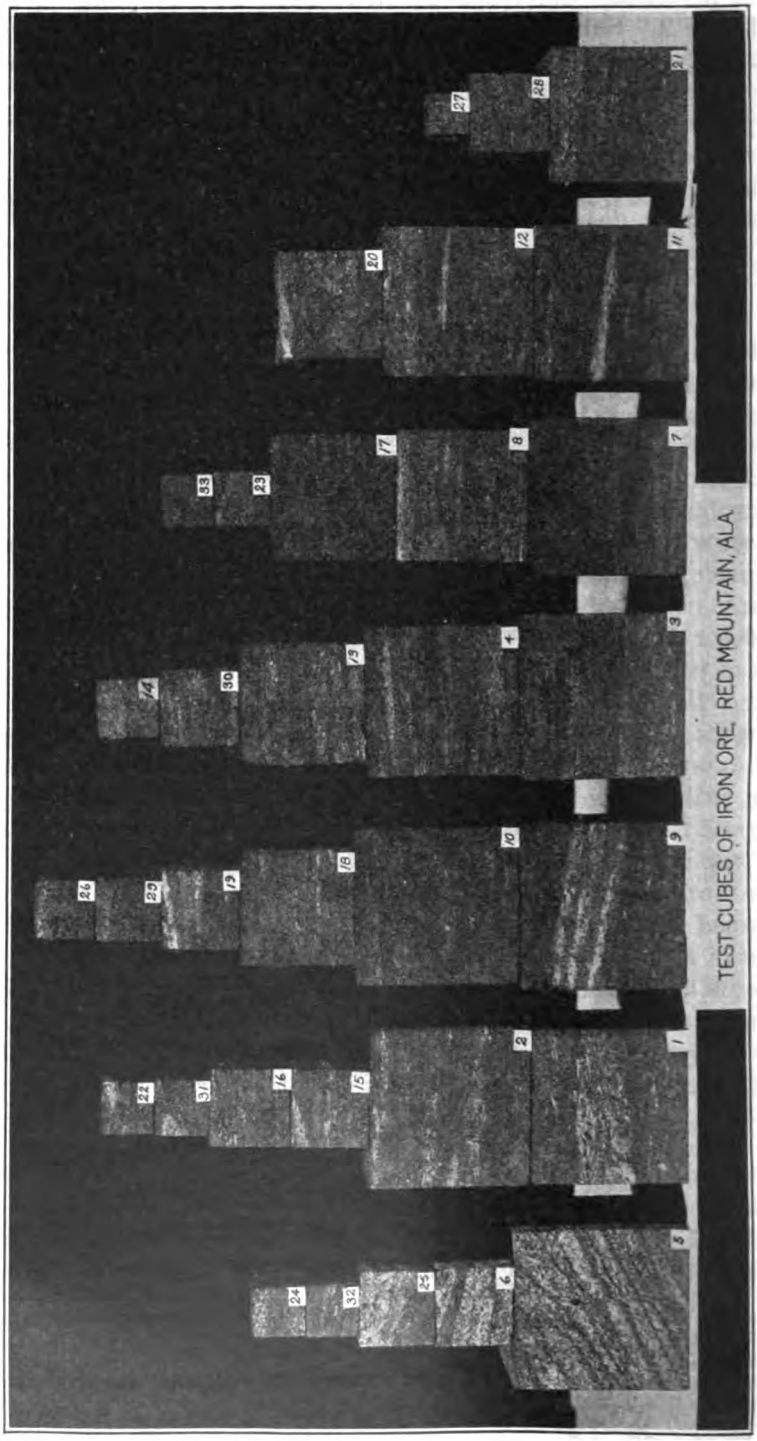

FIGURE 2.—Cubes of ore prepared for testing

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while the final tests, by D. W. Kessler, Bureau of Standards, Department of Commerce, Washington, D. C., were made with a Richle machine of 200,000 pounds capacity.

Doctor Baker gives the angular rupture of stone as 60° with the direction of the compressive force. From measurements of 200 or more iron-ore cubes the writer found that the average angle of fracture was 65.32° with the vertical; however, the larger number of breaks was approximately 60°, the range being from 55° to 80°. Observation of failing pillars shows that the natural angle of fracture is about 60°.

In the preliminary tests the cubes were centered on the bottom rigid plate. The upper plate had a universal or adjustable bearing to conform with possible lack of parallelism between the upper and lower faces of the cubes. In the final tests the plate with universal bearing was placed below to facilitate careful centering of the cubes.

Inequalities in the surfaces of the cubes next to the plates of the testing machine were largely eliminated in both series of tests by the use of hard, dense blotting paper. The efficacy of this material was shown by its adhering to the cube on the ore side and receiving a glossy surface on the upper or plate side.

The results of the tests are shown in Table 3.

TABLE 3.—*Compressive strength of iron-ore cubes* [1]

Cube No.	Section	Height	Area	Breaking load	Strength	Method of testing [2]
	Inches	*Inches*	*Square inches*	*Pounds*	*Pounds per square inch*	
1	3.37 by 3.29	3.42	11.08	106,750	9,640	N
2	3.06 by 3.09	2.96	9.46	124,660	13,170	V
3	3.65 by 3.61	3.44	13.18	143,050	10,850	N
4	3.65 by 3.57	3.45	13.04	206,590	15,850	V-A [3]
5	3.66 by 3.57	3.45	13.08	145,000	11,080	N
6	3.42 by 3.60	3.50	12.32	150,100	12,180	N
7	3.27 by 3.53	3.34	11.55	120,000	10,390	N
8	3.46 by 3.59	3.46	12.42	177,000	14,240	V
9	3.38 by 3.54	3.33	11.97	123,330	10,300	N
10	3.43 by 3.57	3.32	12.25	131,500	10,740	N
11	3.43 by 3.52	3.29	12.08	129,600	10,730	N
12	3.62 by 3.44	3.21	12.46	193,110	15,520	V-A
13	3.55 by 3.61	3.51	12.82	144,950	11,310	N
14	3.65 by 3.50	3.45	12.78	144,850	11,320	N
15	3.76 by 3.51	3.34	13.20	146,300	11,080	N
16	3.76 by 3.47	3.33	13.04	130,650	10,020	N
17	3.51 by 3.85	3.59	13.51	168,400	12,470	N
18	3.97 by 3.50	3.70	13.90	208,750	15,010	V [4]
19	3.77 by 3.46	2.47	13.05	154,900	11,870	N
20	3.82 by 3.47	2.40	13.26	210,200	15,850	V-A [5]
21	3.45 by 2.56	3.26	8.83	86,100	9,750	N
22	3.38 by 2.47	3.42	8.35	125,250	15,010	V
23	3.12 by 3.27	2.72	10.20	95,500	9,360	N
24	3.33 by 3.16	3.26	10.52	175,350	16,660	V-A
25	3.30 by 3.16	3.22	10.42	169,850	16,300	V
26	3.29 by 3.16	2.21	10.39	116,000	11,160	V-A
27	3.20 by 3.31	2.66	10.59	132,000	12,460	N
28	3.32 by 3.36	3.25	11.15	146,140	13,110	V-A
29	3.14 by 3.17	3.10	9.96	101,200	10,160	N

[1] Tests made by the U. S. Bureau of Standards, Department of Commerce, Washington, D. C.
[2] N, tests made under normal conditions; V, tests made under vibration; V-A, tests made with vibratory attachment but without vibration.
[3] Specimen held 1 minute at this load, then broke explosively.
[4] Specimen broke after 2 minutes at this load.
[5] Specimen broke in 15 seconds at this load.

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TABLE 3.—*Compressive strength of iron-ore cubes*—Continued

Cube No.	Section	Height	Area	Breaking load	Strength	Method of testing
	Inches	*Inches*	*Square inches*	*Pounds*	*Pounds per square inch*	
30	3.29 by 2.84	3.22	9.35	109,700	11,730	N
31	3.23 by 2.57	3.28	8.30	142,900	17,230	V
32	3.32 by 2.25	3.30	7.48	81,200	10,850	V-A
33	3.29 by 3.19	3.31	10.49	130,500	12,450	V-A
34	3.33 by 3.35	3.13	11.16	137,800	12,340	N
35	2.85 by 3.29	2.80	9.38	134,320	14,320	V
36	3.30 by 3.32	3.30	10.95	114,650	10,480	N
37	3.32 by 3.27	3.20	10.86	130,300	12,000	N
38	3.29 by 3.31	2.95	10.89	130,600	11,990	V-A
39	3.33 by 3.31	3.33	11.02	112,370	10,190	N
40	3.31 by 3.38	2.61	11.19	147,000	13,140	V
41	3.26 by 3.31	3.27	10.79	108,320	10,040	N
42	3.30 by 2.13	3.03	7.04	65,570	9,310	N
43	3.30 by 3.20	3.31	10.57	138,220	13,070	V-A
44	3.33 by 3.30	3.33	10.99	115,500	10,510	N
45	3.10 by 3.19	2.29	9.89	158,910	16,070	V
46	3.36 by 3.00	3.30	10.08	120,730	11,980	N
47	3.35 by 2.77	3.04	9.28	108,000	11,640	N
48	3.33 by 3.03	3.34	10.09	127,500	12,640	N
49	3.27 by 3.28	2.52	10.72	124,200	11,580	N
50	3.36 by 3.30	3.21	11.09	206,340	18,640	V [6]
51	3.36 by 3.32	3.30	11.15	140,150	12,570	N
52	3.25 by 3.28	2.70	10.67	191,110	17,940	V-A
53	3.59 by 3.54	3.36	12.71	132,900	10,450	N
54	3.57 by 3.39	3.27	12.10	157,200	13,000	V-A
55	3.52 by 3.41	3.22	12.00	119,300	9,940	N
56	3.51 by 3.45	3.29	12.10	125,900	10,400	N
57	3.28 by 3.26	3.17	10.69	165,310	15,460	V
58	3.39 by 3.14	3.16	10.64	103,500	9,740	N
59	3.46 by 3.52	2.59	12.19	184,000	15,100	V-A
60	3.29 by 3.21	3.21	10.56	118,800	11,240	N
61	3.34 by 3.19	3.11	10.66	118,950	11,160	N
62	3.38 by 3.40	3.22	11.50	122,100	10,620	N
63	3.40 by 3.14	3.09	10.68	158,200	14,820	V-A
64	3.51 by 3.36	3.20	11.80	136,000	11,520	N
65	3.42 by 3.39	3.17	11.60	177,940	15,340	V
66	3.58 by 3.41	2.70	12.21	128,700	10,540	N
67	3.48 by 3.24	3.42	11.28	126,400	11,200	N
68	3.39 by 3.18	3.05	10.78	175,150	16,250	V
69	3.44 by 3.31	3.07	11.39	133,400	11,710	N
70	3.41 by 3.24	3.33	11.04	147,310	13,340	V-A
71	3.32 by 3.23	3.45	10.73	123,430	11,500	N
72	3.43 by 3.35	2.55	11.49	115,350	10,040	N
73	3.30 by 3.06	2.91	10.10	162,960	16,140	V
74	3.23 by 3.31	3.33	10.69	100,500	9,400	N
75	3.46 by 3.43	3.40	11.88	190,460	16,020	V-A
76	3.33 by 2.96	3.26	9.86	110,500	11,220	N
77	3.28 by 3.21	3.37	10.52	107,820	10,240	N
78	3.32 by 3.11	3.30	10.32	97,930	9,490	N
79	3.22 by 3.16	3.34	10.18	115,130	11,310	N
80	3.22 by 3.21	3.40	10.34	112,360	10,870	N
81	3.28 by 3.10	3.17	10.17	118,810	11,680	N
82	3.30 by 3.27	3.04	10.78	117,000	10,860	N
83	3.32 by 3.18	3.32	10.55	104,600	9,910	N
84	3.28 by 3.39	3.24	11.12	152,100	13,670	V
85	3.20 by 3.05	2.92	9.77	108,300	11,100	N
86	3.40 by 2.88	2.98	9.80	94,100	9,600	N
87	3.14 by 3.10	3.02	9.74	116,500	11,960	V
88	3.46 by 3.24	3.01	11.21	124,700	11,130	N
89	3.40 by 3.31	3.17	11.26	117,950	10,480	N
90	3.21 by 3.19	3.28	10.24	159,140	15,550	V
91	3.30 by 3.25	3.10	10.72	150,400	14,020	V
92	3.29 by 3.12	3.17	10.26	127,900	12,460	N
93	3.30 by 3.12	3.04	10.30	86,000	8,350	N [7]
94	3.00 by 2.80	3.12	8.40	97,500	11,610	V
95	3.16 by 3.08	3.26	9.75	104,200	10,700	N
96	3.20 by 3.68	3.32	9.86	165,400	16,780	V
97	3.25 by 3.63	3.13	9.85	111,860	11,370	N
98	3.23 by 3.16	2.99	10.21	97,600	9,550	N
99	3.09 by 2.97	3.14	9.18	119,800	13,060	V
100	3.16 by 3.15	3.32	9.96	114,200	11,460	N
101	3.23 by 3.11	2.93	10.04	125,330	12,480	V
102	3.27 by 3.14	3.11	10.26	146,520	14,280	V-A
103	3.31 by 3.21	3.16	10.63	116,500	10,950	N
104	3.09 by 3.09	3.34	9.56	137,570	14,400	V-A
105	3.20 by 3.07	3.29	9.84	97,300	9,890	N
106	3.24 by 3.05	2.92	9.89	102,000	10,320	N

[6] Specimen broke violently after 1 minute at capacity of machine.
[7] Vertical crack.

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TESTS UNDER VIBRATION

Careful study of failing pillars in the mines showed that most failures occur near falls of top rock, which led the writer to conclude that the intense vibration caused by falls might make pillars fail under less pressure than when the load was static. An attempt was made to demonstrate the correctness of this conclusion by subjecting the test pieces to vibratory action and gradually increasing pressure.

The results were surprising in that instead of showing that the ore failed under less pressure the converse was the case. The compressive strength of cubes cut from one mass of ore increased from 10 to 50 per cent over that in the normal tests. Obviously, however, the increase was not due wholly to vibration, therefore duplicate tests were made with the vibratory attachment in place but without the vibratory action. As a result the compressive strength still remained high, being but 3 per cent lower than the strength obtained under vibration, which averaged 28.3 per cent above the strength obtained under normal conditions.

The reason for the relatively large increase in compressive strength under these conditions was easily found. The vibratory attachment consisted of a 6-inch cylinder with a 1½-inch steel plate at the lower end; the upper end rested against the upper plate of the testing machine and was attached to it. Within the cylinder operated a 10-pound hammer actuated by an external mechanism. The cylinder and plate, being lighter and consequently more flexible than the heavy plate of the machine, permitted more perfect contact between the cube and plate; thus more accurate testing was possible.

After higher compressive strengths were obtained with the vibratory attachment in place, a series of tests were made with other cubes, a number of which were duplicates of those tested under normal conditions. As duplicates were not available for all cubes tested, values for N, V, and V–A were calculated and are given in Table 4, except that averages of duplicates for the various feet in a section are given.

TABLE 4.—*Compressive strength of iron-ore cubes prepared from sections of ore taken from mines in the Big Seam, Red Mountain, Birmingham district, Ala., representing each foot of the bed worked, from the top down*

Foot	Section	Height	Area	Breaking load	Strength in pounds per square inch		
					Normal	Vibration	Vibratory attachment
MINE A	*Inches*	*Inches*	*Sq. in.*	*Pounds*			
1	3.35 by 3.13	3.04	10.50	113,312	10,133	13,000	12,696
2	3.22 by 3.10	3.14	9.98	124,188	10,581	13,575	13,258
3	3.26 by 3.14	3.30	10.25	111,042	10,837	13,904	13,579
4	3.22 by 3.11	3.16	10.03	119,978	10,809	13,869	13,544
5	3.28 by 3.22	3.13	10.55	120,500	10,631	13,639	13,320
6	3.30 by 3.08	3.31	10.19	109,160	10,730	13,766	13,445
7	3.20 by 3.06	3.23	9.82	127,153	11,716	15,032	14,680
8	3.18 by 3.09	3.09	9.84	114,232	10,229	13,124	12,816
Average	3.25 by 3.11	3.17	10.14	117,445	10,708	13,738	13,417

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TABLE 4.—*Compressive strength of iron-ore cubes prepared from sections of ore taken from the mines in the Big Seam, Red Mountain, Birmingham district, Ala., representing each foot of the bed worked, from the top down*—Continued

Foot	Section	Height	Area	Breaking load	Strength in pounds per square inch		
					Normal	Vibration	Vibratory attachment
MINE B	*Inches*	*Inches*	*Sq. in.*	*Pounds*			
1	3.58 by 3.46	3.31	12.40	145,050	10,412	13,369	13,067
2	3.51 by 3.43	3.25	12.05	122,600	10,170	13,068	12,743
3	3.31 by 3.20	3.16	10.61	118,875	11,200	14,369	14,033
4	3.52 by 3.46	2.64	12.20	156,350	11,296	14,492	14,303
5	3.33 by 3.20	3.16	10.66	134,405	10,895	13,978	13,651
6	3.46 by 3.37	3.18	11.70	156,970	11,738	15,060	14,708
7	3.39 by 3.27	3.15	11.09	140,150	11,224	14,400	14,093
Average	3.45 by 3.34	3.12	11.53	139,200	10,990	14,160	13,792
MINE C							
1	3.65 by 3.59	3.44	13.11	174,820	11,770	15,075	14,722
2	3.76 by 3.49	3.33	13.12	138,475	10,550	13,536	13,219
3	3.54 by 3.58	3.47	12.70	147,550	11,620	14,871	14,522
4	3.65 by 3.21	3.14	11.81	158,933	11,689	14,997	14,647
5	3.36 by 3.56	3.40	11.96	148,500	10,744	13,785	13,463
6	3.21 by 3.19	3.19	10.27	115,705	9,962	12,769	12,470
7	3.40 by 3.55	3.32	12.11	127,415	10,520	13,497	13,181
8	3.52 by 3.48	3.25	12.27	161,355	11,558	14,829	14,482
9	3.60 by 3.55	3.48	12.80	144,900	11,315	14,517	14,177
Average	3.52 by 3.46	3.33	12.24	146,405	11,078	14,208	13,881
MINE D							
1	3.36 by 3.20	2.73	10.79	139,155	11,310	14,510	14,171
2	3.34 by 3.37	3.36	11.28	145,480	11,092	14,231	13,899
3	3.43 by 3.21	3.23	11.03	150,775	11,933	15,310	14,952
4	3.32 by 3.23	3.45	10.73	123,430	11,500	14,755	14,410
5	3.42 by 3.27	3.20	11.21	140,355	11,178	14,341	14,006
Average	3.37 by 3.26	3.19	11.00	139,839	11,402	14,629	14,287
MINE E							
1	3.22 by 3.21	2.99	10.36	135,425	11,328	14,534	14,194
2	3.29 by 3.16	3.21	10.40	142,925	10,806	13,864	13,539
3	3.26 by 3.33	2.95	10.87	139,070	11,461	14,706	14,361
4	3.14 by 3.17	3.10	9.96	101,200	10,160	13,035	12,730
5	3.26 by 2.70	3.25	8.82	126,300	12,579	16,140	15,763
6	3.31 by 2.93	3.24	9.71	116,500	10,311	13,229	12,920
7	3.07 by 3.30	3.05	10.16	124,485	10,820	13,883	13,558
8	3.30 by 3.29	3.07	10.87	130,450	10,784	13,836	13,513
9	3.30 by 3.33	3.07	11.00	122,563	10,157	13,031	12,727
10	3.30 by 2.66	3.17	8.80	101,895	9,870	12,664	12,367
11	3.33 by 3.30	3.33	10.99	115,500	10,510	13,484	13,169
12	3.27 by 2.98	2.87	9.75	129,213	12,048	15,458	15,096
13	3.32 by 3.20	3.02	10.63	152,680	12,916	16,571	16,194
14	3.30 by 3.30	3.00	10.91	165,630	13,444	17,248	16,845
Average	3.27 by 3.13	3.09	10.23	128,845	11,228	14,405	14,068
Grand average	3.37 by 3.26	3.18	11.02	134,346	11,081	14,216	13,889

More precise testing, with regard to equipment and procedure, may give results showing a still greater increase over those obtained in normal static tests.

That the results obtained approached proper testing conditions more nearly was evident from the failure forms and the angular fracture obtained. In the tests under normal conditions many cubes failed unsymmetrically, half cones and pyramids being formed, but single cones, pyramids, and wedges extending from the top to

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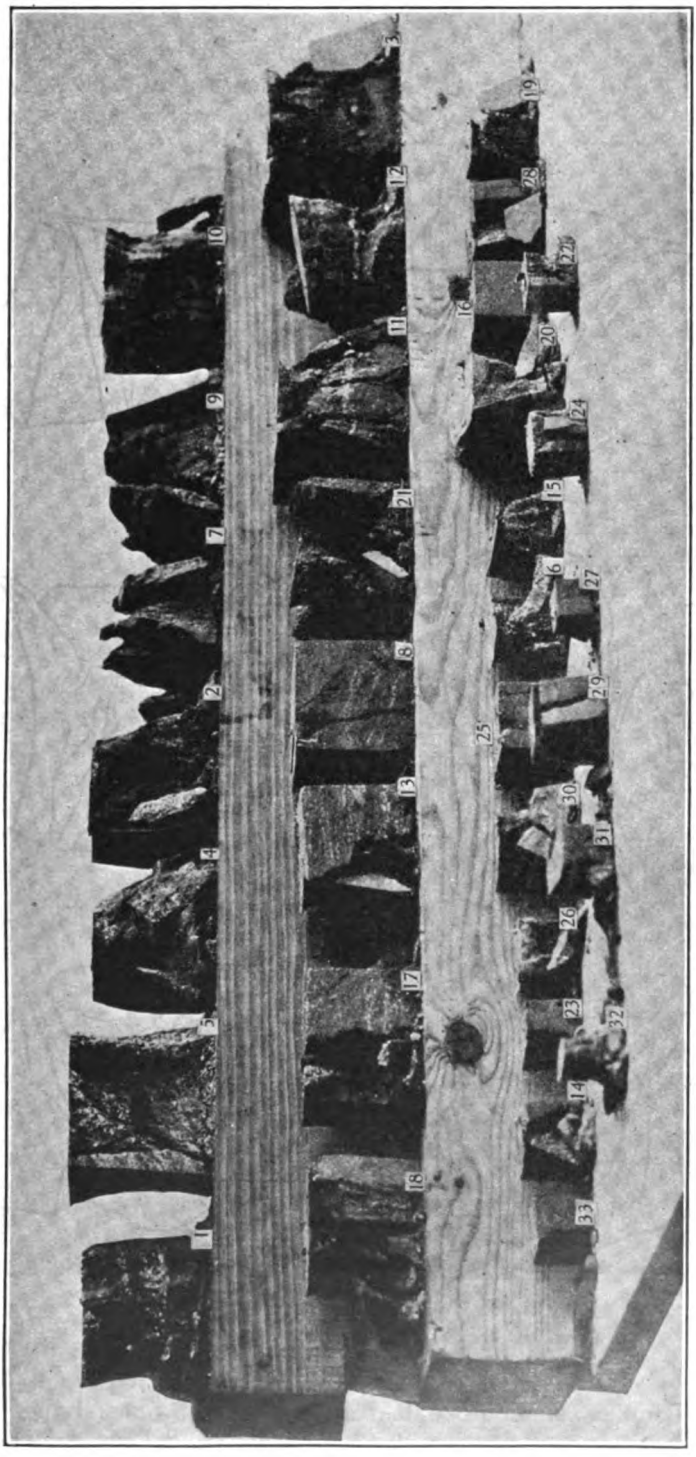

FIGURE 3.—Cubes after testing, showing failure forms

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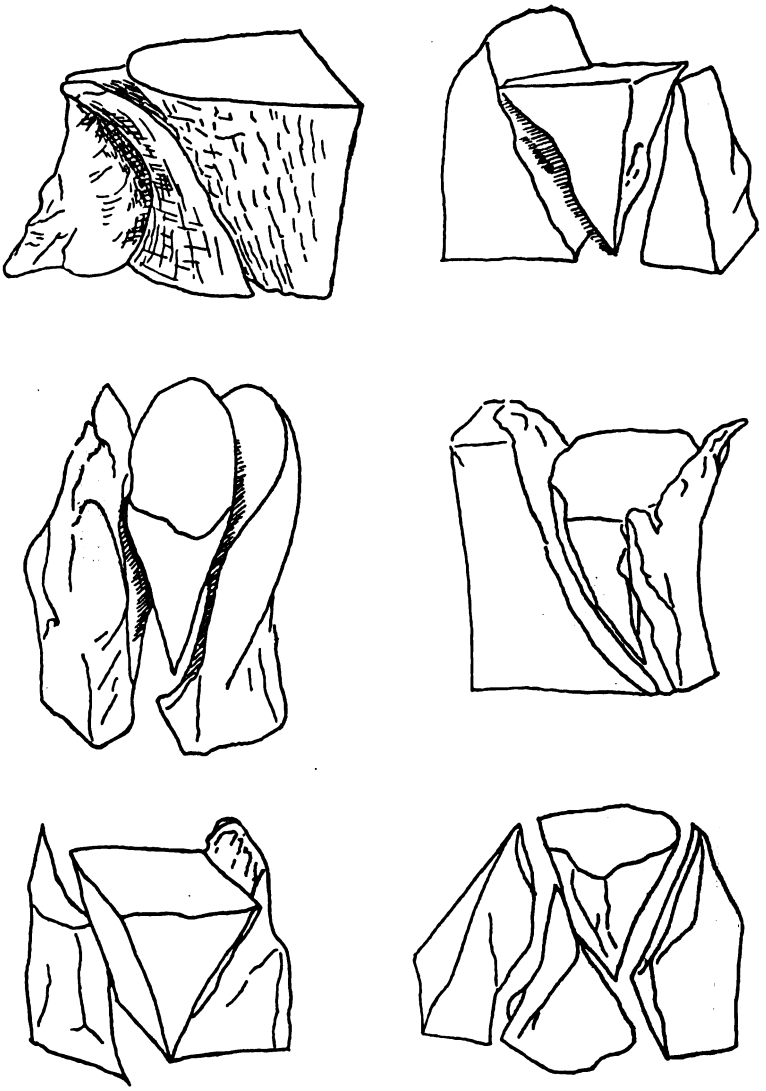

FIGURE 4.—Failure forms resulting from crushing cubes of ore

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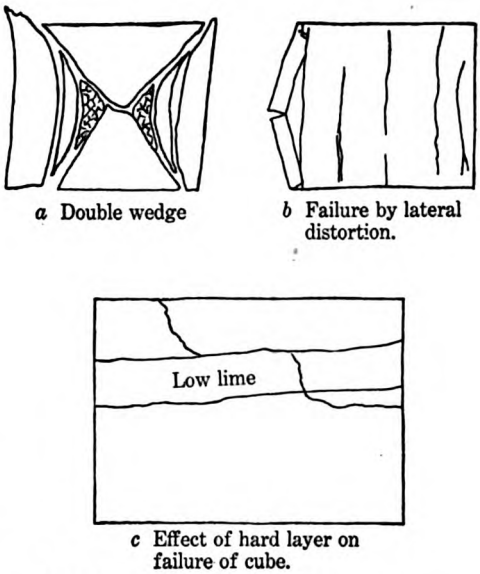
the bottom of the cubes predominated. (See figs. 3, 4, and 5.) When the vibratory attachment was in place and testing was done with or without vibration, symmetrical fractures and the formation of double cones, wedges, and pyramids were the rule. (See fig. 5, *a*.) Further, while the failure of cubes was quiet under normal conditions, it became violently explosive when the vibratory attachment was used. For failure forms in crushing pillars, see Figures 6 and 7.



a Double wedge

b Failure by lateral distortion.

c Effect of hard layer on failure of cube.

FIGURE 5.—Failure of ore cubes under compression

EFFECT OF FRACTURES

To ascertain the influence of defects in the test pieces used, each cube was examined with a microscope before it was tested, and the position and extent of fractures carefully noted. The fractures observed were classified as horizontal, vertical, diagonal, horizontal-vertical, and diagonal-vertical. The compressive strength of

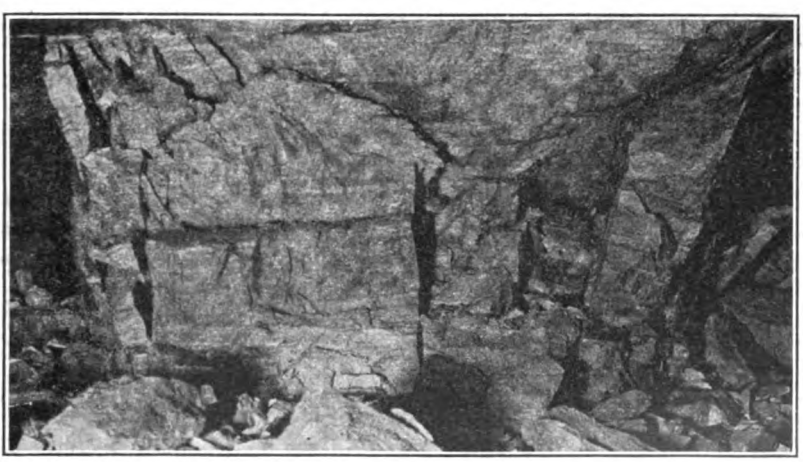


FIGURE 6.—Failing pillar forming inverted cone

cubes with such defects was: Horizontal fractures, 10,918 pounds; vertical, 9,520 pounds; diagonal, 11,156 pounds; horizontal-vertical, 10,000 pounds; and diagonal-vertical, 10,630 pounds per square inch.

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Cubes having no visible fractures gave 10,949 pounds per square inch. The average of all defective cubes was 10,701 pounds and of all non-fractured cubes 10,949 pounds, a difference of 248 pounds per square inch. The lowest strength of the defective cubes was 9,520 pounds, the highest 11,156 pounds per square inch, which would seem to indicate that vertical cracks or fractures weaken the cubes least of all, while the diagonal cracks are most weakening. This condition may, however, be apparent rather than real, as the number of test pieces showing distinctly vertical cracks was small compared with the number showing other classes of defects.

FIGURE 7.—Upright pyramid formed at base of failing pillar

Tests of duplicate pieces from the same location show that the compressive strength varies but little, the difference being due probably to cracks or incipient fractures. Comparative tests of duplicate cubes are given in Table 5.

TABLE 5.—*Comparison of tests of duplicate test pieces of the same form*

	Section	Height	Area	Breaking load	Strength
		Inches	*Square inches*	*Pounds*	*Pounds per square inch*
1	3.51 by 3.85 inches	3.59	13.51	168,400	12,470
	3.97 by 3.50 inches	3.70	12.90	208,750	11,699
2	3.23 by 3.31 inches	3.33	10.69	100,500	9,400
	3.46 by 3.43 inches	3.40	11.88	190,460	12,785
3	3.51 by 3.36 inches	3.20	11.80	136,000	11,520
	3.42 by 3.39 inches	3.17	11.60	177,940	11,956
4	3.29 by 3.19 inches	3.31	10.49	130,500	9,936
	3.33 by 3.35 inches	3.13	11.16	137,800	12,340
5	3.32 by 3.11 inches	3.30	10.32	97,930	9,490
	3.22 by 3.16 inches	3.34	10.18	115,130	11,310
	3.22 by 3.21 inches	3.40	10.34	112,300	10,870
	3.28 by 3.10 inches	3.17	10.17	118,810	11,680

The compressive strengths given above represent normal conditions.

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TESTS OF OTHER FORMS THAN CUBES

To show the effect of the form of test pieces upon the compressive strength of the ore, tests were made with cubes and other parallelepipeds whose dimensions and compressive strength are given in Table 6.

TABLE 6.—*Compressive strength of cubes and other rectangular test pieces*

Test piece	Area	Height	Compressive strength
	Inches	*Inches*	*Pounds per square inch*
Cube, approximately	11.02	3.18	11,244
Square base, height less than sides	10.77	2.69	11,200
Rectangular base, height same as longer side	8.71	3.18	10,666

As the difference in height between the first two forms is only one-half inch, it is not surprising that the compressive strength differs so slightly. The difference is, however, more marked in the form with narrow base—the third in the table.

Doctor Baker[7] gives the following compressive strengths for various stones; for comparison the average compressive strength of iron ore from the Birmingham district has been added:

TABLE 7.—*Compressive strength of stones*

Stone	Ultimate crushing strength, pounds per square inch
Granite	19,379
Limestone	9,438
Marble	12,709
Sandstone	9,333
Iron ore (hematite)	11,081

The compressive strength given for iron ore was found under normal conditions. The compressive strength with the vibratory attachment in place but without vibration is 13,889 pounds per square inch. The latter value is more nearly accurate.

TRANSVERSE STRENGTH OF TOP ROCK

The transverse or bending strength of the top rock largely determines the size of the openings made to extract the ore. The beds of rock forming the roof of workings must act as beams in resisting the weight thrown upon them. Such resistance depends upon the tensile strength of the beds, which is much less than the compressive strength.

[7] Baker, Ira Osborn, A Treatise on Masonry Construction. 1909, p. 11.

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The top rock that forms the roof of the mine workings is composed of slate and sandstone. The latter is often highly ferruginous, and the iron oxide undoubtedly adds materially to its strength. The beds of sandstone within 5 or 10 feet of the top of the ore bed are usually thick enough to constitute strong elements of support, although the beds of shale (locally called slate) are often thinly stratified and weaken on weathering.

Slip and cross-bedding planes adversely affect the conditions of support. They make necessary relatively narrow workings and the use of timber for temporary support. Even when such precautions are taken it often happens that the roof falls in a comparatively short time. When conditions permit, the most satisfactory procedure is to leave roof ore to support the weak shale top rock.

On the whole a reliable index of the strength of top rock and its ability to stand would seem to be the span at which beds of certain thickness will fail of their own weight.

Test pieces were cut from slabs of slate, sandstone, roof ore, and an intermixture of slate and sandstone or roof ore. The test pieces were difficult to prepare, because they disintegrated under the vibration of the saw and the excessive amount of water used in sawing. The selection made probably separated the specimens that had been exposed to air and moisture from those more recently exposed, and the pieces tested were probably more representative of the top rock in place. Of about 50 test pieces that it was planned to test, only 22 were obtained. This limited materially the tests made and the data gathered.

RESULTS OF BENDING-STRENGTH TESTS

Information concerning the bending-strength tests is given in Table 8.

As a number of the specimens were irregular, they were embedded in plaster of Paris. Measurements of the cross section were taken at or near the fractured section, because of variations in cross section throughout the specimen.

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TABLE 8.—*Bending-strength tests of top rock in the roof of ore mines*

Test piece No.	Kind of material	Span (l)	Breadth (b)	Depth (d)	Ultimate load (P)	Modulus of rupture $\left(\frac{S-Mc}{I}\right)$
		Inches	*Inches*	*Inches*	*Pounds*	*Pounds per square inch*
1	Slate	14	3.18	1.20	510	2,340
2	do	14	3.00	1.24	380	1,640
3	do	13	3.12	1.81	710	1,355
4	do	13	2.99	1.70	505	1,140
5	do	12	2.90	1.30	610	2,240
6	do	10	3.00	2.15	750	810
7	do	10	2.95	1.00	110	560
8	do	14	3.00	1.05	270	1,710
9	do	14	2.84	1.55	720	2,220
10	do	14	2.90	1.61	670	1,890
11	do	11	2.95	1.70	910	1,760
12	do	14	3.10	1.69	740	1,750
13	Slate, ore, or sandstone	14	2.90	1.50	500	1,610
14	do	14	3.20	1.65	800	1,930
15	do	14	2.72	2.21	1,610	2,550
16	do	9	3.00	2.20	3,400	3,160
17	Ore	14	3.14	1.65	580	1,430
18	do	14	3.09	1.45	540	1,740
19	do	16	2.80	2.78	1,700	1,890
20	do	14	2.80	2.98	1,750	1,500
21	do	11	3.50	3.32	6,140	2,640
22	do	13	2.93	1.65	810	1,980

The specimens tested were free from slip planes and of fairly uniform thickness, although cross-bedding was evident in practically all of them. The tests were therefore made with test pieces that represented better than normal conditions of top rock, and the results are probably much more favorable than could be expected with equal spans of top rock.

TESTS OF BEAMS FAILING UNDER THEIR OWN WEIGHT

Calculation in feet of the depth of beams with a given span that will fail under their own weight gives the following values:

TABLE 9.—*Limits of depth of beams with given spans, feet*

Span	10.000	20.000	30.000	40.000
Slate:				
Minimum	.160	.641	1.442	2.564
Average	.099	.397	.893	1.590
Maximum	.038	.153	.345	.613
Sandstone or roof ore:				
Minimum	.080	.321	.724	1.284
Average	.061	.247	.558	.990
Maximum	.043	.174	.392	.697
Sandstone and slate:				
Minimum	.071	.285	.643	1.143
Average	.053	.215	.485	.862
Maximum	.036	.145	.327	.582

Table 9 shows that 30-foot spans of the top rocks constituting the roof of the ore mines average failing under their own weight as follows: Slate, 0.89 foot; sandstone or roof ore, 0.56 foot; and slate and sandstone, 0.48 foot. Shale and sandstone or ore intimately interstratified therefore give the most satisfactory roof material.

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MODULUS OF RUPTURE

Table 10 gives the modulus of rupture of several kinds of stone, as determined with the testing machine at the United States arsenal, Watertown, Mass.[8]

TABLE 10.—*Transverse strength of stone*

Stone	Average modulus of rupture, pounds per square inch
Bluestone, North River	5, 026
Granite	1, 849
Limestone	1, 377
Marble	1, 390
Sandstone	1, 378
Slate	7, 671
Iron ore (hematite)	1, 765
Ore and "slate"	1, 863
"Slate"	1, 617

To the above table have been added the results of tests by Prof. J. M. Daniels, at the Carnegie Institute of Technology, of 22 test pieces—12 of slate (shale), 6 of ore, and 4 of ore and slate.

The difference between the two sets of measurements of slate—7,671 and 1,617 pounds per square inch—is probably due largely to the physical condition of the specimens. Practically all of the specimens last tested showed ripple marks and cross-bedding and were thinly stratified.

The test pieces were collected and prepared by the Bureau of Mines for bending-strength tests.

ELASTICITY OF ORE

The tests recorded in this section were made in the United States Bureau of Standards laboratories, Washington, D. C., under the direction of D. W. Kessler. Several columns were cut from masses of iron ore free from fractures, all but one test piece having the larger dimension at right angles to the bedding planes.

The evident failure of pillars through lateral expansion under roof pressure suggested the desirability of determining whether or not lateral expansion or deformation actually took place and if so to what extent. The spalling off of slabs of ore and the loosening of masses of ore as the height of pillars is reduced by roof pressure were checked by the observations made in the testing of cubes and hardly seem to need corroboration by actual deformation tests; however, such tests were made, with the results recorded in the tables that follow.

[8] Baker, Ira Osborn, A Treatise on Masonry Construction. 1909, p. 13.

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The longitudinal compression was measured by a compressometer that consisted of an averaging lever system manipulating an Ames dial reading to one-thousandth inch. Deformation was measured on two opposite faces of the column, and as the lever mechanism gave a magnification of five to one, the actual values are one-fifth those recorded.

To determine the lateral expansion due to vertical compression, measurements were made with a single Ames dial so arranged that it could be shifted to any vertical position on the column. Measurements were taken on opposite faces. The dial read to one ten-thousandth inch and the values given showed actual expansion.

RESULTS OF DEFORMATION TESTS

Deformation tests were made to show the vertical distortion of four columns of ore 4.47, 5.40, 11.88, and 13.29 inches long. The results are given below:

TABLE 11.—*Deformation measurements of 4.47-inch iron-ore column, showing vertical distortion* [a]

[Area of column, 11.22 square inches; bedding, horizontal; gauge length, 3.5 inches]

Load, in pounds:	Inch
40	0.0000
11,220	.0019
22,440	.0033
33,660	.0051
44,880	.0068
56,100	.0089
67,320	.0111
78,540	.0130
89,760 [b]	.0158

TABLE 12.—*Deformation measurements of 5.40-inch iron-ore column, showing vertical distortion* [a]

[Area of column, 11.23 square inches; bedding, horizontal; gauge length, 4.50 inches]

Load, in pounds	First test	Second test	Third test	Fourth test	Fifth test	Sixth test
	Inch	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*
40	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
11,230	.0055	.0055	.0054	.0059	.0045	.0063
22,460	.0101	.0101	.0094	.0101	.0083	.0125
33,690	.0141	.0141	.0136	.0139	.0121	.0161
44,920	.0179	.0183	.0166	.0175	.0159	.0189
56,150	.0218	.0220	.0212	.0209	.0192	.0221
67,380	.0238	.0255	.0231	.0244	.0226	.0257
78,610	.0289	.0294	.0285	.0272	.0255	.0287
89,840	.0305	.0308	.0319	.0308	.0282	----------

[a] Actual values are one-fifth those recorded.

[b] Actual values are one-fifth of those recorded.

[c] Specimen began to crack at this load.

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TABLE 13.—*Deformation measurements of 11.88-inch iron-ore column, showing vertical distortion* [1]

[Area of column, 11.56 square inches; bedding, vertical]

Load, in pounds	9-inch gauge		10½-inch gauge			
	First test	Second test	Third test	Fourth test	Fifth test	Sixth test
INCREASED	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*
40	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
11,560	.0042	.0066	.0049	.0052	.0049	.0050
23,120	.0091	.0119	.0102	.0110	.0120	.0109
34,680	.0151	.0179	.0168	.0173	.0192	.0163
46,240	.0199	.0221	.0224	.0245	.0241	.0230
57,800	.0260	.0271	.0287	.0292	.0333	.0301
69,360	.0321	.0330	.0351	.0358	.0397	.0356
80,920	.0378	.0389	.0419	.0418	.0457	.0419
92,480	.0438	.0435				
DECREASED						
69,360				.0377		.0370
57,800				.0330		.0311
46,240				.0265		.0254
34,680				.0206		.0195
23,120				.0147		.0135
11,560				.0083		.0073

[1] Actual values are one-fifth those recorded.

TABLE 14.—*Deformation measurements of 13.29-inch iron-ore column, showing vertical distortion* [1]

[Area of column, 11.36 square inches; bedding, horizontal]

Load, in pounds	10-inch gauge		11¼-inch gauge			
	First test	Second test	Third test	Fourth test	Fifth test	Sixth test
INCREASED	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*
40	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
11,360	.0140	.0111	.0108	.0101	.0101	.0103
22,720	.0231	.0200	.0226	.0211	.0219	.0210
34,080	.0318	.0282	.0320	.0305	.0311	.0307
45,440	.0387	.0362	.0400	.0400	.0407	.0399
56,800	.0460	.0439	.0500	.0483	.0497	.0495
68,160	.0534	.0517	.0584	.0565	.0588	.0569
79,520	.0610	.0587	.0672	.0650	.0678	.0661
90,880	.0689	.0650	.0764	.0732		
102,240	.0760	.0731				
DECREASED						
90,880	.0712					
79,520	.0651		.0695			
68,160	.0583		.0639			
56,800	.0518		.0557			
45,440	.0450		.0485			
34,080	.0375		.0408			
22,720	.0290		.0329			
11,360	.0195		.0232			

[1] Actual values are one-fifth those recorded.

The results of these deformation measurements show a fair degree of uniformity, and the values for elastic measurements of different test pieces show about the same range as were obtained in the compressive tests.

There was less vertical distortion in the column with bedding planes vertical than in the column of about the same height with the bedding horizontal; there was, however, greater vertical distortion in the shorter columns with bedding horizontal.

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LATERAL EXPANSION

Measurements of lateral expansion under vertical compression were made on a 13.29-inch column. Two series of tests are shown.

TABLE 15.—*Measurement of lateral expansion of 13.29-inch iron-ore column; bedding, horizontal* [1]

Load, in pounds	¼ inch from end	1 inch from end	2 inches from end	3 inches from end	4 inches from end	5 inches from end	6 inches from end	At center end
TEST 1	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*	*Inch*
56,800	----------	0.00167	0.00100	0.00059	0.00122	0.00171	0.00070	0.00080
90,880	----------	.00212	.00218	.00116	.00191	.00218	.00088	.00158
TEST 2								
56,800	0.00018	----------	.00091	.00028	.00031	.00102	.00085	----------
90,880	.00050	----------	.00121	.00115	.00111	.00180	.00128	----------

[1] Actual values not recorded.

Results of the lateral expansion tests were not altogether satisfactory. It is probable that the number of tests made was too small and some of the test pieces may have been defective. Lateral expansion occurs, but is least in the middle of the column and greatest at or near the ends. How far lateral expansion contributes to the failure of pillars is, then, not definitely known, but it probably plays an important part. Figures 8 and 9 show the effect of lateral expansion.

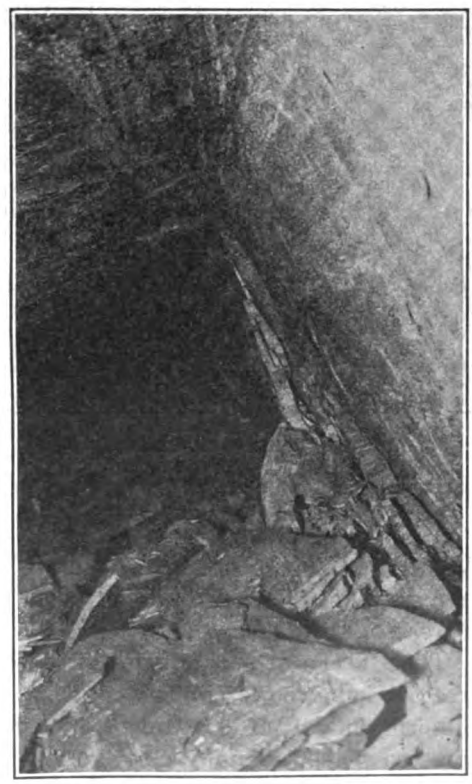

FIGURE 8.—Ore spalling from face of pillar

MODULUS OF ELASTICITY

The modulus of elasticity of stone varies with the load and is valuable in determining the distortion of a mass of stone or ore under weight. With ore the modulus of elasticity may give some indication of the distortion that will result under the weight of superincumbent strata.

Iron ore, like sandstone, takes a permanent set for all loads. Ferruginous sandstone naturally does the same.

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TABLE 16.—*Modulus of elasticity of stone between limits of 100 to 1,000* [3]

Stone	Pounds per square inch
Granite	4, 639, 000
Limestone	4, 675, 000
Marble	6, 949, 000
Sandstone	2, 212, 000
Iron ore (hematite)	7, 500, 000

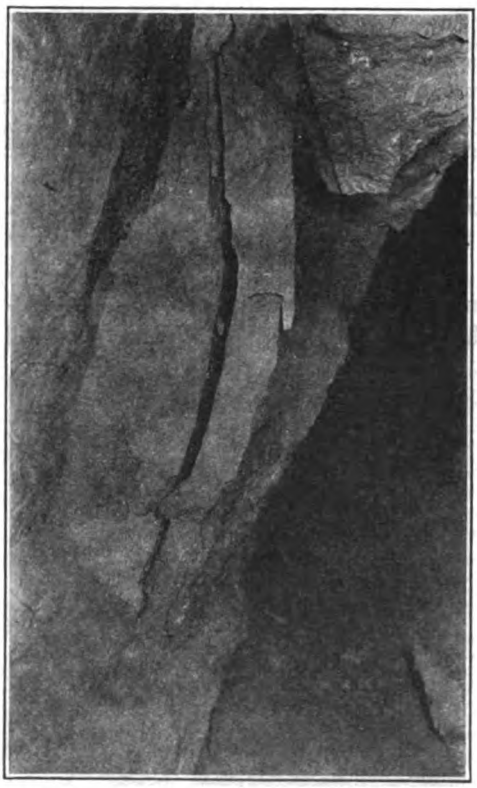

FIGURE 9.—Failure of pillar by distortion

The modulus of elasticity given for iron ore has been added to the table for comparison and is an average of 8 or 10 tests, the range being from 6,110,000 to 9,640,000. The tests were made between limits of 100 to 9,000 pounds per square inch.

The modulus of elasticity or compressibility is determined by dividing the length of a bar or column of material subjected to longitudinal pressure by the decrease in length and multiplying the quotient by the load in pounds per square inch. The amount by which a test piece fails to return to its original size and shape on the release of pressure has been defined as "set." It represents permanent distortion.

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[3] Baker, Ira Osborn, A Treatise on Masonry Construction. 1909, p. 14.

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